Dusty, Radiation Pressure Dominated Photoionization. II. Multi-Wavelength Emission Line Diagnostics for Narrow Line Regions

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ABSTRACT

Seyfert narrow line region (NLR) emission line ratios are remarkably uniform, displaying only ∼0.5 dex variation between galaxies, and even less within an individual object. Previous photoionization and shock models of this region were unable to explain this observation without the introduction of arbitrary assumptions or additional parameters. Dusty, radiation pressure dominated photoionization models provide a simple physical mechanism which can reproduce this spectral uniformity between different objects. In the first paper of this series we described this model and its implementation in detail, as well as presenting grids of model emission lines and examining the model structures. Here we explore these models further, demonstrating their ability to reproduce the observed Seyfert line ratios on standard line diagnostic diagrams in both the optical and UV. We also investigate the effects that the variation of metallicity, density and ionizing spectrum have upon both the new paradigm and the standard photoionization models used hitherto. Along with the standard diagnostic diagrams we provide several new diagnostic diagrams in the UV, Optical and IR. These new diagrams can provide further tests of the dusty, radiation pressure photoionization paradigm as well as being used as diagnostics of the metallicity, density and ionizing spectrum of the emission line clouds.

Subject headings: galaxies: active — galaxies: Seyfert — ISM: general — line: formation

1. Introduction

The emission lines of active galaxies have often been used in conjunction with models to constrain the physical and ionization structure of the emitting regions. In particular

ratio diagrams or line diagnostic diagrams prove to be an excellent visual aid in interpreting the emission line data. First used systematically by Baldwin, Phillips, & Terlevich (1981), line diagnostic diagrams take the observed ratios from emission line galaxies and create a two-dimensional classification scheme which is better able to differentiate between excitation mechanisms and determine other properties of emitting regions such as density or chemical abundance in the gas phase. The line diagnostic diagrams by Veilleux & Osterbrock (1987) are particularly useful as they involve ratios of lines which are not greatly separated in wavelength and so minimize the effects of differential reddening by dust within the emission line region. These diagrams are capable of distinguishing three different groups of emission line galaxies: those excited by starbursts and two classes of object excited by an active nucleus - the Seyfert narrow line regions (NLRs) and the low ionization nuclear emission-line regions (LINERs). These diagrams are additionally interesting in that they show that the emission from NLRs is remarkably uniform, with only ∼0.5 dex variation between Seyferts and less within individual galaxies. This uniformity of the spectral properties has since been confirmed in much larger samples (eg Véron-Cetty & Véron 2000).

The use of line diagnostic diagrams (LDDs) is not limited to distinguishing the excitation source of active galaxies. They can also help us understand the details of the physical processes going on within the ionized nebulae by comparing observations with the predictions of both photoionization and shock models (Evans & Dopita 1985; Dopita & Sutherland 1995). The best fitting models can, in turn, indicate the physical parameters and excitation mechanisms of the NLR.

Such comparisons have led to the acceptance of both of the mechanisms for excitation in narrow line regions. However, excitation by fast, radiative shocks (Dopita & Sutherland 1995, 1996) appears mostly in the extended NLR (ENLR) associated with radio galaxies and in LINERs, and is applicable only for a few Seyfert galaxies. The photoionization models, and variations thereof (e. g. Komossa & Schulz 1997; Binette et al. 1996, 1997; Baldwin, Ferland, Korista, & Verner 1995; Ferguson et al. 1997), are able to reproduce the Seyfert observations with only a few failings. The main problem with the standard photoionization models is that they are unable to provide the observed uniformity in emission line ratios without making arbitrary (and possibly unphysical) assumptions. The less than 0.5 dex variation in observed line ratios requires an approximately constant ionization parameter of $U \sim 10^{-2}$, where the ionization parameter is a measure of the number of ionizing photons against the hydrogen density ($U = S_{\star}/\mathrm{n_H}c$). Since there is no physical reason why the ratio of photon density to gas density should be constant within a given Seyfert, or from one Seyfert to another, such a result is puzzling to say the least. Furthermore, many Seyferts show strong coronal lines of highly ionized species which can only be produced in a plasma with $U \gtrsim 1.0$. So why do low and intermediate excitation species indicate $U \sim 10^{-2}$?

In order to account for these failings of the standard models we have proposed a new paradigm for the photoionization of the NLR clouds, that of dusty, radiation pressure dominated photoionization (Dopita et al. 2002, hereinafter DG02).

We have demonstrated previously that this model provides a self-consistent explanation for the remarkable similarity between the emission line spectra of NLR. The radiation pressure acting upon the dust provides a simple controlling factor for the moderation of the density, excitation and surface brightness of the emission line region. This limits the models of the low- and intermediate-excitation line ratios at high ionization parameters to $\sim$0.5 dex in the line diagnostic diagrams, but allows the coexistence of high ionization parameter and low density regions within a single model.

Following the introduction of this model, we gave details on how this model was implemented within the photoionization & shock code MAPPINGS III and a grid of UV, Optical and IR emission lines, covering a range in metallicity, density, power-law ionizing continuum and photoionization parameter (Groves, Dopita & Sutherland 2003, Paper 1 of this series). We also examined the physical structure of the dusty model and how this varied with the different input parameters.

We continue this work here, presenting line diagnostic diagrams for both our dusty model and the standard photoionization model derived from the line ratios given in Paper 1.

2. Dusty, Radiation Pressure Dominated Models

The inclusion of dust into photoionization models affects the final emission spectrum in several ways. As well as simply absorbing EUV radiation and competing with Hydrogen for the ionizing photons, dust affects the temperature structure of the NLR clouds through the process of photoelectric heating.

In order to be physical, an isobaric photoionization model must include the effects of radiation pressure. The force of radiation can be imparted to both the gaseous medium and dust, and results in a radiation pressure gradient. Since the grains are charged and are therefore locked to the plasma by coulomb forces, the radiation pressure gradient on dust results in a gas pressure gradient identical in size. Standard photoionization models are isochoric and therefore cannot take this effect into account. To demonstrate these effects we have run the standard isochoric model and the new dusty, radiation pressure dominated model over a large set of input parameters.

With simple calculations it is easy to show that at an ionization parameter of $\log U \sim -2$, dust begins to dominate the opacity of the ionized cloud and hence the radiation pressure. It is also around this value of the ionization parameter that radiation pressure developed at the ionization front of the NLR cloud becomes comparable with the gas pressure. Therefore at high ionization parameters, the pressure in the ionized gas, and hence density (since the electron temperature is always $\sim 10^4$K), is determined by the external ionization parameter, U_0 and the local ionization parameter becomes independent of the external ionizing flux. The result of this is that at high ionization parameter the emission line spectrum of the low- and intermediate ionization species is effectively independent of the external ionization parameter. This independence was illustrated through the example line diagnostic diagrams (LDDs) given in DG02 and is demonstrated again in this paper.

Once the exciting mechanism of the NLR of the active galaxies has been clearly identified, the diagnostic line ratio plots will also be useful in defining the physical conditions within the NLR. To facilitate this, we have run a series of the dusty, radiation pressure dominated models covering a range in density, metallicity, power-law index of the ionizing spectrum, and photoionization parameter. To provide a comparison we also present a series of dust-free, standard photoionization models covering the same range of parameters. We described the implementation of these models in depth in Paper 1 of this series (Groves, Dopita & Sutherland 2003), where we gave the emission line strengths from these models in a sequence of tables covering the parameter space. These tables were used to construct the diagnostic plots presented here.

2.1. Parameter Space

The parameters were chosen to cover the range of values that would be reasonably expected to be found in the NLR of Seyfert galaxies. The spread in parameter space allowed an examination of how each parameter affected the models, and was great enough that the resulting line emission from each model was distinct.

Three Hydrogen number densities (n_H) were modeled; $n_H = 10^2,\ 10^3$ and $10^4\ cm^{-3}$. For the standard isochoric (constant density) models such modeling is straightforward. However for the isobaric, dusty, radiation pressure dominated models the concept of a single density for the nebula no longer holds. Thus we have used the region near the ionization front, where $n_{HII}/n_{HI} \sim 1.0$, as the fiducial point at which to set the density. It is in this region that the density sensitive lines like [S II]$\lambda\lambda 6717, 30$Å or [O II]$\lambda\lambda 3727, 9$Å are at their strongest and so this region defines the effective electron density that line observations will measure.

Five Metallicities were examined in the models; $0.25Z_\odot$, $0.5Z_\odot$, $1Z_\odot$, $2Z_\odot$ and $4Z_\odot$. The abundance set adopted for solar metallicity is given in table 1. The individual abundances of most elements scales with the metallicity, $X/H = Z \times (X/H)_\odot$. The two contrary elements are Helium and Nitrogen. For Helium, the chemical yield from stars adds only a small amount to the primordial abundance,

$$\mathrm{He/H} = 0.0737 + 0.0293\mathrm{Z/Z_\odot} \tag{1}$$

The nucleosynthetic status of Nitrogen is unusual in that it has both primary and secondary nucleosynthetic components. The Nitrogen abundance at different metallicities is given by;

$$[\mathrm{N/H}] = [\mathrm{O/H}]\left(10^{-1.6} + 10^{(2.33+\log_{10}[\mathrm{O/H}])}\right). \tag{2}$$

The origin of this and equation 1, as well as the justification for the Solar abundance set are discussed in Paper 1.

Because dust is present, the gas-phase abundances are depleted in comparison to the total abundances. The depletion fractions adopted are given in Table 2. In the new radiation pressure dominated models the metals are depleted onto the dust, but for the dust-free standard models this depletion is artificial, with the metals effectively lost. This is done to ensure that the gas phase abundances in both sets of models are the same, because the heavy elements in the gas phase determine the cooling to a large extent and also have some effect upon the ionization state within the nebula.

We use a simple power-law to represent the spectral energy distribution (SED) of the ionizing source, with

$$F_\nu \propto \nu^\alpha \quad \nu_{\min} < \nu < \nu_{\max}. \tag{3}$$

and $\nu_{\min} = 5$eV and $\nu_{\max} = 1000$eV. We investigated four values of the power-law index α, -1.2, -1.4, -1.7 and -2.0. These indices encompass the 'standard' values usually adopted for modeling of the AGN spectrum. The factor of proportionality, which determines the total radiative flux entering the photoionized cloud is set by the ionization parameter at the front of the cloud, $U_0 = S_\star/(n_0 c)$, where $S_\star$ is the entering flux of ionizing photons, n_0 the initial density and c the speed of light.

This ionization parameter is the final parameter allowed to vary in this family of models, with $\log U_0$ varying between 0.0 and -4.0, sampled at intervals of -0.3, -0.6 and -1.0 dex. For the standard isochoric models the initial density is a known quantity and hence the ionization parameter at the front of the cloud is easy to determine. In the dusty, isobaric models the initial density is not known *a priori*. To estimate this value we assume a front end temperature of $T_0 = 20,000$ K and obtain the density from the set P_0. Depending

upon the temperature reached at the front of the model, the true density will vary, being overestimated at higher temperatures and underestimated for cooler temperatures. This means that the true ionization parameters in the upper range ($\log U_0 > -2.0$) are actually larger than that given in the text, and are smaller for the lower range ($\log U_0 < -2.0$). The general shape of the curves in the line diagnostic diagrams is still correct. However, the true range of ionization parameters is somewhat larger than indicated on these diagrams.

3. Diagnostic Diagrams

There are several considerations we must take into account in the choice of line ratios to use in the line diagnostic diagrams (LDDs). These are:

1. The lines must be strong enough to be measurable in most Seyferts.

2. The line diagnostic diagram must provide physical insight into the nature of the emitting system. For example, the LDDs put forward by Veilleux & Osterbrock (1987) provided clear diagnostics of the excitation mechanism, with NLRs, LINERs and H II galaxies well separated. Another good example are the UV diagnostics of Allen, Dopita, & Tsvetanov (1998) which are able to discriminate between photoionization models, shock models, and shock+precursor models.

3. To minimize wavelength sensitive effects such as reddening and flux calibration, the wavelength separation between the lines that make up the ratio should be as small as possible. For reddening this becomes more important at shorter wavelengths, especially around the 2200Å extinction feature seen in our galaxy.

4. The lines should be all observable using a common instrument and the same technology. For example, a UV line ratio versus a Visible line ratio may be a good diagnostic, but it is highly unlikely that one could ensure the same aperture for these observations. Hence line ratio diagrams should be made up of ratios that lie within a single wavelength regime easily accessible by the same instrument.

5. Emission lines which are usually blended with other lines must be either avoided or taken as a blend, as deblending lines can greatly increase the uncertainty of the measured flux.

6. One should avoid the use of lines which carry large flux errors resulting from the theoretical models used. An example of this is [O I]λ6300Å which, though easily measurable, is highly dependent upon the point at which the model has been truncated.

3.1. Standard Optical Diagnostic Diagrams

The line diagnostic diagrams put forward by Veilleux & Osterbrock (1987) (V&O) have become standard diagnostics for emission line galaxies. This is because the diagrams not only consist of the some of the strongest emission lines which are easily accessible to ground base telescopes, but they also clearly distinguish between the excitation mechanisms of the emission line galaxies.

Figure 1 shows the first of the V&O diagrams; [N II]λ6583/Hα versus [O III]λ5007/Hβ. Figure 1a demonstrates the effect of different metallicities upon the dusty models, with the Seyfert 2 observations from the original V&O paper given for comparison. The models plotted are for a density of 1000 cm^{-3} and a power law index of $\alpha = -1.4$, and cover a range in ionization parameter of $-4.0 \leq \log U_0 \leq 0.0$. Lines of constant ionization parameter are marked and labelled at set intervals. Each model curve represents a different metallicity, increasing from left to right, with the metallicity of each curve labelled. Also indicated on the diagram is the effect of reddening upon the models. The direction and magnitude of the arrow indicates the effect of an external dust screen with 10 magnitudes of visual extinction using the reddening curve from Calzetti (2001) (their equation 8). The diagram reveals the large spread in the [N II]/Hα ratio for the set of photoionization curves, which is largely due to the varying contributions of the secondary component of Nitrogen nucleosynthesis. A comparison of the photoionization curves with the observational data also reveals that most of the NLR in Seyfert galaxies are characterized by super-solar metallicity, with a mean value of about 2 $Z_{\odot}$. The sub-solar curves are unable to reproduce the data.

Using this information, figure 1b compares both the dusty models and the standard, dust-free isochoric models with the observational data. The different sets of models are labelled and cover a range of power-law index from $\alpha = -1.2$ to -2.0. Both sets of models have a metallicity of 2 $Z_{\odot}$ and n_{H}=1000 cm^{-3}, with each model curve ranging from $\log U_0 = -3.0$ to 0.0. For both sets of models, as the power-law becomes flatter (i.e. harder spectral energy distribution), the trajectories of the models are displaced from the bottom-left towards the top-right region of the diagram. The dusty models “stagnate” in the region occupied by the observational data at high ionization parameter. That is, as the ionization parameter increases, the dusty models tend to return the same values for the ratios, and become degenerate in terms of U at the highest values. As for the dust-free models, [N II]/Hα decreases continually with increasing ionization parameter, as the overall ionization state of the gas increases. This behavior provides a clear distinction between the models and is one of the principal reasons successes of the dusty, radiation pressure dominated photoionization models, as discussed in Dopita et al. (2002).

There are several other points to note within the diagram. One is the difference between

the behavior of the two sets of models in the [O III]/Hβ ratio at low ionization parameter. At high ionization parameter a difference is expected due to the effects of extinction by dust and radiation pressure on dust, but at low ionization parameter such effects should be minimal as dust is no longer the dominant opacity. The difference between the models arises due to the definition of the ionization parameter at the front of the cloud, as discussed in §2.1. In the case of $\log U_0$ of -3.0, the dusty models overestimate the effective ionization parameter due to the overestimate of the assumed initial temperature. Hence the dusty models display a weaker [O III]/Hα ratio than the dust-free set. The apparent difference is therefore an artifact of the initial condition, and should be ignored. The lack of observational points below $\log U_0 \sim -3$ is not a failing of the models, rather it is due to the definition of Seyfert 2 galaxies. The region below that occupied by the Seyferts is not empty, rather it contains the class of galaxies classified as LINERs (see eg. V&O). LINERs may include a subset which could be considered low power Seyferts, but they also include shock excited emission line galaxies and possible old starbursts as well, and thus we have not considered these within our sample.

The other point to note is the spread in model sets due to the variation in power-law index, α. For both sets of models a flatter (harder) ionizing spectrum leads to an increase in both ratios, especially [O III]/Hβ. This is due to the increase in photons available to ionize these higher ionization species compared to hydrogen. At low ionization parameter, the region covered on the diagram by the models of different power-law index is similar to that found for models with different metallicity. This indicates the limited utility of these ratios as either a Z or an α diagnostic. At high ionization parameter however, the variation of α is clearly distinguished from that of Z in the dusty models, with the models at different α curving in upon each other such that they deliver little spread in the [O III]/Hβ ratio or the [N II]/Hα ratio. The observational data is well covered by the models, and the most reasonable values of α probably lie in the range $-1.4 < \alpha < -1.2$.

Figure 1c shows the V&O diagram [O I]λ6300/Hα versus [O III]λ5007/Hβ, with the data points being taken again from the same paper. Though the strength of the [O I]λ6300 line may not be entirely trustworthy for the reasons discussed previously, the line is strong and easily measured and the ratio proves to be a good diagnostic. As discussed in Paper 1, our models are truncated at the point at which H II/H ratio drops below 1%, such that the final temperature is a few 100 K. This means that the majority of the O I emitting region is encompassed within the model as the emission of O I drops below 1000K. Figure 1c demonstrates the effect of variation of metallicity on both the dusty and the dust-free models. The models have U_0 ranging from 10^{-3} to 10^{0}, with α fixed at -1.4 and the density at 1000 cm^{-3}. The metallicity increases from $0.25 Z_{\odot}$ for the leftmost curve to $4 Z_{\odot}$ on the right. As both line ratios are ratios of oxygen to hydrogen lines, any variations are due to changes in

the temperature and ionization of the gas. The multi-valued nature of the curves arises due to the combination of two effects. As metallicity increases, the strength of the metal emission lines initially increases due to the increase in abundance. However, increasing the metallicity also increases the cooling efficiency of the gas and hence lowering the temperature. At high ionization parameter, there is a clear distinction between the dusty and dust-free models, as seen in the previous diagrams. The dusty model line ratios stagnate in a limited zone of parameter space, while the dust free models display a large decrease in the [O I]/Hα ratio with increasing ionization parameter. As in the previous diagnostics, the observed data points are best fit by the dusty models, with the curves at high ionization all clustered in the region of interest. The data is best reproduced by the curves with a metallicity of $Z = 1 - 2Z_{\odot}$, but, because oxygen is a primary rather than secondary nucleosynthesis element, the distinction between the curves of different metallicity is not as clear as in the case of the [N II]/Hα ratio.

Figure 1d shows the effects of variation of α upon the dusty model ratios. The models all have $Z = 2Z_{\odot}$, $n_{\rm H} = 1000$ cm^{-3}, and each curve covers the range $-3.0 \leq \log U_0 \leq 0.0$. Each curve represents a different power-law index, as labelled. This diagram more clearly demonstrates the spread due to α at low metallicities, and the convergence of the models in a narrow strip of parameter space, similar to that seen in figure 1b. Though not shown here, the dust-free models also appear very similar to the dust-free curves of figure 1b as well. This diagram clearly indicates how well the dusty models reproduce both the clustering and the absolute values of the observational data. A value of α between -1.4 and -1.9 provides the best fit to the observed range of observational points.

The final V&O diagram is [S II]$\lambda\lambda$6717, 30/Hα versus [O III]λ5007/Hβ. Figure 1e demonstrates the effects of metallicity variation upon the two sets of models, while figure 1f demonstrates the effects of power-law index variation upon both. Both figures use the same set of fiducial parameters as before.

In most ways these diagrams are similar to the previous figures. They display a large spread due to metallicity and power-law index, and show similar shapes to the previous model curves. At high ionization parameter, the dusty and dust-free models separate as in the previous figures, with the dusty models displaying the same stagnation in the region of interest. The observational data is similarly best reproduced by the dusty models, with a metallicity $Z \sim 1Z_{\odot}$ and a power-law index $\alpha \sim -1.4 - -1.7$. Note that though the $Z \sim 1Z_{\odot}$ seems to better fit the data when metallicity variation is considered, the diagram of the α variation (using $Z = 2Z_{\odot}$ to remain consistent) demonstrates that the variation in power-law index may also be quite large.

Of the three V&O diagnostic diagrams, the [N II]λ5683/Hα is the clearest metallicity diagnostic thanks to the effects of the secondary nucleosynthetic component of the nitrogen

production. It has well separated metallicity curves that cover a range which is much broader than that due to power-law index variations. This means that it is not degenerate with α as the other two diagrams are. This diagnostic diagram shows that the mean metallicity in Seyfert NLRs is $\sim 2Z_{\odot}$ although it may truly range from $1Z_{\odot}$ up to $4Z_{\odot}$. The result of a higher metallicity is not surprising, as the new abundance set used and the depletion by dust both act to reduce the gas abundance compared to previous models. A value of $\sim 2Z_{\odot}$ is approximately the same as the old Solar values (Anders & Grevesse 1989), as has been estimated previously for NLR metallicity.

An estimate of the average power-law index can be obtained by consideration of all three diagrams. In these, the range $-2.0 \leq \alpha \leq -1.2$ encompasses all of the observed data, but more typical values of the index range between -1.4 and -1.7.

The mean density of the Seyfert NLR clouds is harder to determine as all three diagnostic diagrams show small variation due to density at high ionization parameters when compared to the effects of the other parameters, especially metallicity.

The self-consistency of the modelling is demonstrated by the fact that the observed ratios on all three diagnostic diagrams are reasonably reproduced by the same set of parameters, with a very broad range of ionization parameters able to reproduce the tight clustering of the data.

3.2. Standard UV Diagnostic Diagrams

Whilst the optical diagnostic diagrams provide an excellent tool for separating starburst galaxies from those with an AGN, these optical line ratios are unable to conclusively distinguish between shocks and photoionization as an excitation mechanism for active galaxies. Ultraviolet emission lines, however, tend to be much stronger in shocks than in simple photoionization models and hence much better diagnostics for shock and photoionization separation. This difference is due to the collisionally excited lines in the UV, like C IV λ1549, having increased emission at the higher temperatures found in post-shock gas (Dopita & Sutherland 1995, 1996, and references therein). This temperature sensitivity also proves to be useful in distinguishing between classical photoionization models and the dusty models presented in this paper.

A further benefit of UV diagnostic diagrams is that in high redshift active galaxies, the UV emission lines are shifted to the optical band, and can be observed with ground-based telescopes. Hence the UV diagnostic diagrams are better for determining the excitation mechanism of the high-z galaxies than the standard optical ones which may be difficult or

impossible to observe.

UV diagnostic diagrams have been developed and explored in the case of high-Z radio galaxies by Villar-Martin, Tadhunter, & Clark (1997) and comparisons of shock and photoionization models have been made by Allen, Dopita, & Tsvetanov (1998) (hereafter ADT). Here, we continue this exploration and comparison with the inclusion of dusty photoionization models.

The first three UV diagrams of Villar-Martin, Tadhunter, & Clark (1997) use three UV line ratios; C IV λ1549/C III]λ1909, C IV λ1549/He IIλ1640 and C III]λ1909/He IIλ1640. The observational data on each figure comes from ADT, with the stars marking the high-z radio galaxy (HZRG) observations and the triangles representing HST observations of three nearby Seyferts NGC 1068, NGC 5643 and NGC 5728. In addition to the observational data each figure is marked by an arrow indicating the size and direction of the reddening vector by a foreground dusty screen with an A_V of three magnitudes. As for the previous section, the Calzetti (2001) curve is used for reddening correction.

Figure 2 shows the effect of metallicity variation on the C IV λ1549/C III]λ1909 versus C IV λ1549/He II λ1640 diagnostic diagram. The models all have a power-law index of $\alpha = -1.4$, and density $n_{\rm H} = 1000\,{\rm cm}^{-3}$. Each curve covers a range in ionization parameter of $-2.3 \leq \log U_0 \leq 0.0$, with each having a different metallicity as labelled. The range of ionization parameter shown here is smaller than in the optical diagrams as C IV rapidly weakens for $U < 10^{-2}$. As in the optical diagrams, the line ratios stagnate at high ionization parameter in the region where both the HZRGs and the Seyfert galaxies lie. They also stagnate in metallicity as both line ratios reach their maximum value at $Z \sim 1Z_\odot$. Any value between $0.25Z_\odot < Z < 2.0Z_\odot$ is equally effective in reproducing the observations. A metallicity less than solar may even be plausible for the HZRGs which are observed at early stages of galaxy formation.

Following the format of the optical diagnostic diagrams, figure 2b demonstrates the effects of power-law index variation upon both the dusty and dust-free models at a metallicity of $2Z_\odot$, and $n_{\rm H} = 1000\,{\rm cm}^{-3}$. The index becomes steeper from top to bottom on the diagram for both sets of models and the ionization parameter covers the same range as before. Little can be inferred from this diagram other than that both the dusty and dust-free models provide an equally good fit to the observational points. However, it is significant that there are no observational points above log(C IV/C III]) > 0.6, just above the point where the dusty models stagnate.

As discussed in Paper 1, care must be taken with these UV diagnostics due to the presence of resonance lines like C IV. The radiative transfer of these lines is not treated

exactly within the photoionization code, but rather approximated with an escape probability, which includes the opacity effect of dust. This means that there is a larger error associated with the ratios which involve these lines and they should be treated as less certain.

The second UV diagnostic diagram is C IV $\lambda1549$/C III]$\lambda1909$ versus C III]$\lambda1909$/He II$\lambda1640$, shown in figure 2c, where the effect of metallicity variation upon these line ratios in the dusty models is demonstrated. Again all curves have $\alpha = -1.4$ and $n_{\rm H} = 1000\,{\rm cm}^{-3}$ with $\log U_0$ ranging from -3.0 to 0.0. The shape and form of these curves are very similar to that found in figure 2a. Here the effect of metallicity variation is once again more apparent at low ionization parameters, but both metallicity and ionization parameter become degenerate at high ionization parameter. All that can be said is that the dusty models fit the data points in the range $\log U_0 > -2.5$ and $Z \lesssim 2.0 Z_\odot$.

In figure 2d we assume a $2Z_\odot$ metallicity to compare the dusty models with the dust-free models for these ratios. Shown in this comparison is the effect of density variation on these two models. The power-law index is -1.4 and ionization parameter is $-3.0 \leq \log U_0 \leq 0.0$ for these sets of models. In both sets of models the density increases from $10^2\,{\rm cm}^{-3}$ at the bottom to $10^4\,{\rm cm}^{-3}$ at the top. Clearly, although some density sensitivity is present, the spread due to metallicity or spectral index is just as large and hence these parameters cannot be separated by the use of these ratios alone. Nonetheless, it is clear that the dusty photoionization models provide a much better description of the range of observations than do the dust-free models.

The third Villar-Martin, Tadhunter, & Clark (1997) diagram has C III]$\lambda1909$/He II$\lambda1640$ versus C IV $\lambda1549$/He II$\lambda1640$. As before, we demonstrate first the effect of metallicity upon these ratios for the dusty model, in figure 2e, using $\alpha = -1.4$, $n_{\rm H} = 10^3\,{\rm cm}^{-3}$ and $-3.0 \leq \log U_0 \leq 0.0$. Though rotated and flipped relative to the previous diagrams, the curves on this diagram show a similar form to that seen on both the other two diagrams.

Finally, figure 2f shows the effect of α variation with these ratios on both sets of models, using the standard $Z = 2Z_\odot$, $n_{\rm H} = 1000\,{\rm cm}^{-3}$ and $-3.0 \leq \log U_0 \leq 0.0$. The power-law index increases from left to right in both sets of models. This also has the same general form as the previous diagrams. Once again, the line ratios of the dusty models stagnate in U_0 and Z in the region occupied by the observational points. These dusty models provide a much better fit to the observations than the dust-free models.

Allen, Dopita, & Tsvetanov (1998) also provided several other diagnostic diagrams, mainly with the purpose of distinguishing shock excitation from photoionization. These diagnostics also prove to be valuable in further establishing the validity of the dusty, radiation pressure dominated photoionization models.

Figure 3a shows the sensitivity to metallicity and ionization parameter of C IV λ1549/C III]λ1909 versus C II]λ2326/C III]λ1909. The empty triangles represent the Seyfert galaxies shown in the previous UV diagnostic diagrams. This figure is somewhat more useful in distinguishing between different metallicities, but unlike the previous three UV diagnostics, it appears to indicate a metallicity greater than $2Z_{\odot}$. Another possibility is that these galaxies may also have some shock component to them, which, as seen in figure 2d of ADT, would bring the models closer to the observations.

This diagram is also somewhat sensitive to the power-law index, as shown in figure 3b, which displays both the dusty and dust-free models are displayed with $2Z_{\odot}$, $n_{\rm H} = 10^3\,{\rm cm}^{-3}$ and $-3.0 \leq \log U_0 \leq 0.0$. Clearly, the dusty models once again provide a better description of the observations than the dust-free models, which have too weak C II]/C III] ratio and too strong C IV/C II] ratio at high ionization parameter.

In figure 4a we examine an optical-near UV diagnostic, [Ne V]λ3426/[Ne III]λ3869 versus [O III]λ5007/Hβ. The effect of metallicity variation upon these ratios in the dusty models is shown in figure 4a. Though the spread is small compared to some of previous UV diagnostics, this diagnostic has the additional benefit of the minimal error and reddening in the [O III]/Hβ ratio. Included on the diagram are three observational data sets. The empty triangles represent the Seyfert galaxies from the previous UV diagrams. The crosses are data from four Seyfert 2 galaxies from Allen (1998). The asterisks represent observations of Seyfert 2 galaxies from the data set of Koski (1978). All three sets of data are consistent with a metallicity somewhere between $1Z_{\odot} \leq Z \leq 4Z_{\odot}$. Although the dusty models stagnate in terms of the ionization parameter in the region occupied by the data, not as much can be inferred from this because the dust-free models are multi-valued in U_0 in this region as well. This is shown in figure 4b, which plots curves of different α for the two models at $Z = 2Z_{\odot}$, $n_H = 1000\,{\rm cm}^{-3}$and $-2.6 \leq \log U_0 \leq 0.0$. α increases with increasing [O III]/Hβ. The two sets of models differ in their behavior in α, with the dusty model curves stagnating in a very restricted region of parameter space but the dust-free models becoming more widely separated. The fact that the stagnation point of the dusty models agrees with the observational points gives further credence to the general validity of this class of models.

In addition to the ADT paper there have been more recent investigations of UV diagnostics, such as Inskip et al. (2002a,b) who used the diagnostics to examine high redshift ($z \sim 1$) radio galaxies. The redshift of these galaxies brought several of the UV diagnostic lines into the optical range, making them accessible to ground based telescopes, with long enough integration times. Due to the fact that these galaxies have very energetic expanding radio lobes, they are expected to be excited by both shocks and by nuclear photoionization. Being able to distinguish between these differing excitation mechanisms is important in our

understanding of these high-z AGN.

The UV diagnostic diagram chosen by Best, Röttgering, & Longair (2000b), and expanded by Inskip et al. (2002a), combines the same neon line ratio of the previous diagram; [Ne III]λ3869/[Ne V]λ3426 but plotted against the UV carbon line ratio C III]λ1909/C II]λ2326. This diagram is very good for distinguishing between shock excitation and photoionization. It also turns out to be very good for distinguishing between the dusty models and the dust-free models (figure 5a). The HZRG observations from Inskip et al. (2002a) (their figure 14) are marked on the diagram. Triangles indicate the 6C radio galaxies and stars the 3C radio galaxies. The ionization parameter is restricted to the range $-2.3 \leq \log U_0 \leq 0.0$ because [Ne V] is a very high ionization species and becomes very weak at lower ionization parameters. Figure 5a shows the sensitivity of the emission line ratios to the metallicity. Again, many of these radio galaxies sit in the region of the diagram that is consistent with high ionization parameter; $\log U_0 \gtrsim -1.0$. However, little can be inferred about the metallicity. The radio galaxies with weak C III]/C II] ratios (which are believed to be shock or shock+precursor excited (Best, Röttgering, & Longair 2000a,b; Inskip et al. 2002a,b)) cannot be reproduced by these dusty models without resorting to very high ($Z > 4Z_\odot$) metallicities. This is similar to figure 3.

Figure 5b demonstrates the use of this diagram in distinguishing between dusty and dust-free photoionization models. The model curves, with $Z = 2Z_\odot$, $n_{\rm H} = 1000\,{\rm cm}^{-3}$, vary in power-law index, ranging from -1.2 at low C III]/C II] to -2.0 for the models with high C III]/C II]. The dusty models are clearly able to reproduce the HZRG observations that are believed to be photoionized, whereas the dust-free models would imply a much flatter power-law ($\alpha < -1.2$) or else a higher metallicity to even approach the observational points.

Though our ability to derive a clear definitive set of parameters for the Seyfert Galaxies and the high redshift radio galaxies is limited in these UV diagnostic diagrams due to the degenerate nature of many of the curves, one detail stands out in all diagnostics; the dusty, radiation pressure dominated models provide undeniably the better fit to the observations over the standard dust-free models. In all cases the dusty models not only reproduce the data well, but also tend to become degenerate in terms of the ionization parameter precisely in the region occupied by the observations.

3.3. Further Useful Diagnostic Diagrams

The previous sections demonstrated the utility of the dusty, radiation pressure dominated models. We will now explore several new or relatively unexplored line ratio diagrams,

not only to gain a deeper understanding of the dusty photoionization models but to also find diagrams which can provide diagnostics of the metallicity, density and the slope of the ionizing power-law.

These diagrams extend the wavelength base from the far-UV into the near and mid-IR. They adhere to the guidelines of Veilleux & Osterbrock (1987) re-iterated at the start of section 3. The program used to create these diagnostics is available at `http://www.mso.anu.edu.au/~bgroves/linedata`. Also available there is the model data used to create these diagnostics, which were discussed in depth in Paper 1. This includes the standard, dust-free, undepleted models discussed in Paper 1, if the readers wish to examine the diagnostic diagrams of this model.

For the dusty models we adopt a fiducial model which has a metallicity of $2Z_{\odot}$, a power-law index of $\alpha = -1.4$ and a density of $n_{\mathrm{H}} = 1000\,\mathrm{cm}^{-3}$ following the results of the previous sections. Each of these parameters is adjusted separately to determine the sensitivity of each line diagnostic to each parameter in turn. For the ionization parameter, the greatest possible range is explored. This turns out to be quite restricted for the line ratios which involve high ionization species.

3.3.1. UV Diagnostics

The benefits of UV diagnostics in providing insight into the physics of high redshift active galaxies and in distinguishing between photoionization and shock excitation has been examined in depth in earlier works by Villar-Martin, Tadhunter, & Clark (1997); Allen, Dopita, & Tsvetanov (1998); Best, Röttgering, & Longair (2000a,b) and Inskip et al. (2002a,b). However, with the deeper surveys of high redshift galaxies currently underway, we can expect that diagnostic plots involving lines in the far-UV will soon become even more useful.

The first far-UV diagnostic takes two line ratios from ADT; C III λ977/C III]λ1909 and N IIIλ991/N III]λ1750. Both ratios are temperature sensitive and hence are good at separating shock excitation from photoionization (see figure 3 of ADT). When plotted against a ratio which increases steadily with U_0, such as C IV λ1549/C III]λ1909 they also provide reasonably good metallicity diagnostics, although the spread due to α or $\mathrm{n_H}$ are similar in range. Both of these line ratios have a similar dependence on the electron temperature. Thus, when plotted together, variations in the metallicity, power-law index and ionization parameter are relatively indistinguishable. However, the ratios do provide a diagnostic which is able to distinguish variations in the density, as shown in figure 6. This arises mainly through the nitrogen ratio. The N III]λ1750 line can be represented as a five level system, containing

the lines that make up the 1750 line and a fine structure line at 57 μm. As the density increases, the timescale for collision from the fine structure level becomes less than the emission timescale, and the flux that would normally be emitted through 57 μm, is emitted at 1750 Å. As the C III λ977 resonance line is reasonably unaffected by density, this ratio becomes density sensitive. The density sensitivity is reversed at low U due to the lower temperature and hence lower collisional excitation rate.

One problem with these ratios though is that the reddening is quite large due to the short wavelengths of the lines and the large wavelength separation between numerator and denominator. Corrections due to reddening are also quite uncertain at these short wavelengths, hence the absence of the reddening arrow on figure 6. The small ($\sim$ 0.1 dex) separation between the three densities and the likely large absolute flux errors resulting from the uncertain reddening corrections means that this diagram is probably not useful as a density diagnostic.

In figure 7 we plot C IV λ1549/C III]λ1909 versus C IIIλ977/N IIIλ991. These line ratios are much less sensitive to both temperature and reddening than those used in the previous diagram. The sensitivity to α is also minimized as a consequence of the insensitivity to temperature. The ratios also show very little variation due to density changes. However the C III/N III ratio is quite sensitive to changes in metallicity. This is thanks to the secondary nucleosynthetic component of the nitrogen abundance. The C IV/C III] ratio is primarily useful in distinguishing between different values of U_0. In addition to the effects of metallicity variations, what is also visible is the stagnation at high values of U_0 due to dust and the radiation pressure upon it.

Figure 8 exploits the metallicity dependence further by plotting C III]λ1909/N III]λ1750 versus C IIIλ977/N IIIλ991. Whereas the previous diagram only separated metallicity on one axis, here both axes are ratios of C/N and show large separation between metallicity curves. In addition, the reddening corrections are small, since both pairs of lines are closely separated in wavelength. Thus we have a reasonably sensitive metallicity diagnostic. The only failing of this diagnostic is the short wavelengths of the C III/N III ratio which may make this diagnostic difficult to observe.

Our final far-UV diagnostic diagram also provides a metallicity diagnostic, plotting O VI$\lambda\lambda$1032, 8/C IVλ1549 versus N Vλ1240/C IVλ1549 (figure 9). This diagnostic diagram should prove to be useful in several ways. Firstly, it involves only strong lines and is thus easily measurable. Secondly, the response of the curves to α and $n_{\rm H}$ variations is negligible compared to the metallicity variations. Thirdly, the sensitivity of the O VI/C IV to ionization parameter is strong. Thus this diagram provides an excellent metallicity and ionization parameter diagnostic for photoionized narrow line clouds.

3.3.2. Optical Diagnostic Diagrams

The optical spectral range is easy to observe and provides a large number of lines from which to form diagnostics. Many of these line ratio diagnostics are either temperature or density sensitive as well.

Figure 10 plots the near-UV ratio [Ne V]λ3426/[Ne III]λ3869 against the density sensitive ratio [O II]$\lambda\lambda$3727, 9/[O III]λ5007. We show both the density and ionization parameter dependence of both the dusty and dust-free models. The density increases with decreasing [O II]/[O III] ratio, from 10^2 cm^{-3} at the top to 10^4 cm^{-3} at the bottom. Included on this diagram are the observations of Seyfert 2 NLRs from Koski (1978) (asterisks) and Allen (1998) (crosses). Note that some of the Koski sample has been removed due to contamination by starbursts (see, eg Kewley et al. 2001) Within this diagram the oxygen ratio provides sensitivity to density variations, while the neon ratio provides sensitivity to ionization parameter. Though density variations generate a strong response in the [O II]/[O III] ratio, changes in the other parameters also have some consequences. Variation in the power-law index affects the [Ne V]/[Ne II] ratio (as seen in figure 5a) and may be confused with the effects of density and ionization parameter. In terms of metallicity changes, the only major effect is seen at high U_0 in the dusty models, where it creates a similar spread in the [O II]/[O III] ratio to density. So, overall, this diagram provides a reasonable density diagnostic. What is obvious from figure 10 is that this diagram is able to strongly distinguish between the two sets of photoionization models. The large separation at high ionization parameter clearly demonstrates the success of the dusty model in reproducing the observations. This diagnostic ability is largely due to the [O II]/[O III] ratio and arises because of the differences in density structure of the isochoric, dust-free model and the isobaric, dusty model.

The use of this ratio as a model diagnostic is explored further in the next diagram, figure 11, which plots [O II]$\lambda\lambda$3727, 9/[O III]λ5007 against [O III]λ5007/Hβ. This diagram was one of the original diagnostic diagrams suggested by Baldwin, Phillips, & Terlevich (1981) and has also been used by Binette et al. (1996) to explore the $A_{M/I}$ model. In our figure both the dusty and dust-free models have been plotted, displaying curves of different power-law index. In both cases a flatter power-law corresponds to an increase in the [O III]/Hβ index. The observations of Koski (1978) and Allen (1998) are displayed using the same symbols as the previous diagram. In this diagnostic, the [O III]/Hβ provides a standard diagnostic ratio which helps to separate the two models, as well as distinguish the different α curves. The applicability of the [O II]/[O III] ratio as a model diagnostic is clear in this figure, with the two model sets separating above $\log U_0 = -2.0$. The dusty model curves characteristically stagnate in ionization parameter above this value, becoming degenerate in U_0 in the region occupied by the observations. The dust-free models continue past this region to proceed to

smaller values of the [O II]/[O III] ratio.

In the next diagram, figure 12, we use the [O II]/[O III] ratio to introduce another model diagnostic ratio, He IIλ4686/Hβ. This diagnostic diagram was first introduced by Binette et al. (1996) to distinguish the $A_{M/I}$ model, as it was the failings of the standard photoionization model to reproduce the observed NLR He II/Hβ ratios that led to the development of this model. The He II/Hβ ratio is distinct in the diagnostic ratios examined so far in that it is the dust-free models which stagnate at high ionization parameter, not the dusty models. In figure 12 we display curves of different α for both of these models, with α increasing from right to left. The stagnation of dust-free model in the He II/Hβ ratio at high ionization parameter can be seen in the way the two model sets diverge. The way in which the dusty model stagnates in the [O II]/[O III] ratio at high U_0, while still heading towards larger values of the He II/Hβ ratio, reproduces the observations extremely well, especially in comparison to the inverse behavior seen in the dust-free models. The success of the dusty model in attaining the high He II/Hβ ratio with the observed [O II]/[O III] values comes from its ability to maintain both a high and low-ionization zone at high ionization parameter. This is similar to the main idea of the $A_{M/I}$ model, except it is dust which provides the absorbed spectrum not "matter bound clouds". The absorption by dust further assists by preferentially removing the H ionizing photons to the He ionizing ones, and hence increasing the He II/Hβ ratio.

Figure 12 is also able to distinguish α, with a large spread in the curves across the He II/Hβ ratio, especially in the dust-free models. Density variations cause similar effects to that seen in figure 10, with the [O II]/[O III] ratio providing most of the sensitivity. The influence of metallicity is interesting, as it appears to be negligible in the dust-free models, yet the dominant parameter in the dusty models at high ionization parameter.

The consequences of metallicity variations upon the He II/Hβ ratio are better seen in figure 13, which consists of He II λ4686/Hβ versus the temperature sensitive ratio [O III]λ4363/[O III]λ5007 (R_{OIII}). The Koski (1978) and Allen (1998) observations are included for comparison. On the diagram we display the effects of metallicity variation upon the dusty models. The effect of metallicity variation is predominantly seen in the R_{OIII} ratio. An increase in the metallicity results in a decrease in the nebula temperature and thus a decrease in R_{OIII}, as metals dominate the cooling processes in nebulae. These affects are discussed in detail in Paper 1. In the He II/Hβ ratio the effects of metallicity are not obvious until $U_0 > 10^{-2}$. Although the change in abundance affects the He II emission, the change in emission with metallicity at high U_0 is caused by the change in temperature and the increase in dust. As shown in §5.1 of Paper 1, an increase in metallicity leads to drop in temperature in the He II zone relative to the Hβ emitting region, and hence an increase in the recombination to He II

relative to H. However this effect only contributes ∼10% to the spread. The major effect is due to the increase in the dust to gas ratio because of the increase in metal abundance. This increases the total dust opacity, which preferentially removes the H ionizing photons to the He ones (see figure 2 in Paper 1), thus increases the He II emitting column relative to the H II column and hence the He II/Hβ ratio. The spread in model curves is not seen at low ionization parameter because the dust is no longer the dominant opacity and hence does not control the emitting column.

The [O III]λ4363/[O III]λ5007 (R_{OIII}) ratio is actually one of the standard line ratios, used because of its strength and temperature sensitivity. Figure 14 shows a standard diagnostic diagram plotting R_{OIII} against [O III]λ5007/Hβ. Shown are the effects of density variation on both the dusty and dust-free models, with density increasing from left to right at $\log U_0 = -3.0$. Included with the usual Koski (1978) (crosses) and Allen (1998) (asterisks) observations, are data from Tadhunter, Robinson, & Morganti (1989) (triangles), who specifically looked at the "Temperature problem"; the inability of photoionization models to reproduce the high R_{OIII} ratio. This failure is easily seen in the way the dust-free model curves wrap around at high U_0, not reaching the high R_{OIII} region occupied by the data. What can also be seen in the figure is the success of the dusty models in attaining R_{OIII} values similar to those observed. This success is due to several reasons, the main being the hardening of the spectrum by dust absorption and the contribution of photoelectric heating by dust to the temperature.

Combining two of the previous ratios, the He II/Hβ versus R_{OIII} diagram is one of the more powerful diagnostic diagrams. As shown in figure 10 in Evans et al. (1999), it clearly separates the different possible excitation mechanisms. It is also a diagram in which the standard photoionization model conspicuously fails to reproduce the observations, being too cool to get strong R_{OIII} and unable to attain the strong He II/Hβ. Figure 15 demonstrates this failure, along with the success of the dusty, radiation pressure dominated models in reproducing strong He II/Hβ. Curves of different density have been plotted for both models sets, with density increasing with increasing R_{OIII}. There is a clear separation between the dusty and dust-free models, with the dusty models turning over in both ratios before the observations are reached. In this instance, the dusty models have too low a R_{OIII} ratio to successfully reproduce the observations. A flatter power-law and lower metallicity can better reproduce the observations due to the increase in temperature and the increase in He II ionizing photons, but such changes disagree with the previous diagnostic diagrams. The data itself may also be in error due to the possibility of overestimating such a weak line like [O III]λ4363 (especially in comparison with a strong one like λ5007). Either way this diagram indicates that the models still require some further examination. The dust alleviates part of the temperature problem, but some additional heating source is still needed, such as

small shocks or turbulent heating.

The He II/Hβ diagnostic series continues with He II/Hβ versus [O III]λ5007/Hβ in figure 16. This use of the standard diagnostic ratio provides a clear distinction between the two models, plotted here with density the varying parameter. In both models the higher density corresponds to a stronger [O III]/Hβ ratio. This diagram is a simple and clear justification of the dusty model over the dust-free one.

The final diagnostic diagram in the He II/Hβ series is against [N II]λ6583/Hα in figure 17. In 17a we show dusty model curves of different metallicity, along with the Koski (1978) and Allen (1998) data. The use of [N II]/Hα as a metallicity diagnostic has been discussed previously but here the He II/Hβ provides a clear ionization parameter diagnostic. This enables a better determination of the metallicity, as well as U_0.

As a model diagnostic this diagram is also very good, as demonstrated by figure 17b. The variation due to density in both models is negligible when compared to the separation of the dusty and dust-free model curves at high ionization parameter ($U_0 > 10^{-2}$). Even the dispersion due to metallicity variations provides only small confusion in distinguishing the two photoionization models. At low ionization parameter ($U_0 < 10^{-2}$), the models become indistinguishable as the effects of dust and radiation pressure on dust are relatively small below this value. The data from Koski (1978) and Allen (1998) again agree with the dusty model.

The next optical diagnostic diagram examines the partially ionized zone of the NLR clouds described in Paper 1 by analyzing the low ionization states of oxygen and nitrogen. Figure 18 plots [N I]λ5200/[O II]$\lambda\lambda$7318, 24 versus [O I]λ6300/[N II]λ6583 for both sets of models, with density decreasing from left to right for both model sets. As mentioned before, the low ionization species like O I and N I are somewhat untrustworthy in the models due to their dependence upon the model termination point, which is at the point where H is less than 1% ionized in our models. However the twisting nature of these diagnostic curves make this diagram worth investigating. As expected, for $\log U_0 < -2.0$ the models are very similar, but above this value they diverge. The dust-free model curves turn back upon themselves, heading towards small values of the [N I]/[O II] and [O I]/[N II] ratios. The dusty models continue to increase in both ratios, largely because the partially ionized region continues to grow in the dusty models with U_0, as the dust opacity acts to harden the ionizing spectrum.

The next diagram (figure 19) definitively demonstrates the effectiveness of the dusty models. The ratios [S II]$\lambda\lambda$6717, 30/Hα versus [N II]λ6583/Hα are plotted for the dusty models, displaying the curves of different metallicity. These two ratios together effectively

display what was seen with the Veilleux & Osterbrock (1987) curves. When the ionization parameter ranges over $-4.0 \leq \log U_0 \leq 0.0$ the dust-free models cover a range of 3 dex in both ratios (as can be seen in figure 1). For the dusty, radiation pressure dominated models however, over this large range in ionization parameter each metallicity curve only covers a range of ∼0.5 dex in both ratios. Even more indicative is that this region of stagnation is the same region as occupied by the observations.

The final optical diagnostic diagram considers the combined ratio [O II]$\lambda\lambda 3727, 9 \times$[S II]$\lambda\lambda 6717, 30$ /[S II]$\lambda\lambda 4067, 76 \times$[O II]$\lambda\lambda 7318, 24$. In figure 20 the variations in density for the dusty models are plotted on this ratio versus the ionization parameter diagnostic [O III]$\lambda 5007$/Hβ. The [O II][S II]/[S II][O II] ratio minimizes the effects of variations in both metallicity and power-law index, as the sensitivity of each ratio is cancelled out by its inverse. The ratio has both sulfur and oxygen, and short and long wavelength emission lines on both numerator and denominator, leaving a ratio which experiences little influence from abundance variations and reddening. What it does leaves is a ratio strongly dependent upon density, clearly demonstrated in figure 20.

Though the previous diagrams are only a small sample of the possible optical diagnostic diagrams, they provide enough diagnostics such that they can distinguish the excitation mechanism and verify that the dusty, radiation pressure dominated model is the correct paradigm for photoionization. Together they can also provide estimates for the parameters that define the nebulae; density, metallicity and ionizing spectral energy distribution.

3.3.3. Near-Infrared Diagnostic Diagrams

Though the Near-Infrared experience little extinction due to dust, there is a scarcity of strong lines in this spectral region and thus limited choices for diagnostics. The noble elements, Ne and Ar dominate this spectral region and provide good diagnostic emission lines as they are not depleted onto dust.

The first diagnostic, figure 21, plots [Ne VI]$\lambda 7.652\mu$m/[Ne II]$\lambda 12.8\mu$m versus [Ar VI]$\lambda 4.53\mu$m/[Ar II]$\lambda 6.98\mu$m and displays the effects of variation of α upon the dusty model. Note that as they both contain emission lines from high ionization species, the ratios from the model rapidly disappear as the ionization parameter becomes small ($U_0 < 10^{-2}$). The IR diagnostic diagram is similar to both the UV and optical diagrams in that it demonstrates the stagnation of the dusty models at high ionization parameter. It also shows the same divergence of the dusty and dust-free models above $\log U_0 = -2.0$, though not indicated here. This particular diagnostic diagram

is interesting in that it displays a strong sensitivity to variations in α, with both the influence of metallicity and density being negligible. The sensitivity to metallicity is removed through having ratios of the same element, making this diagram a very good diagnostic of the ionizing SED. The sensitivity to α arises from the difference in ionization states of the numerator and denominator in both ratios.

The next diagram also displays a similar sole sensitivity to α. Figure 22 plots [Ne VI]$\lambda 7.652\mu$m/[Ne II]$\lambda 12.8\mu$m versus [Ar III]$\lambda 8.98\mu$m/[Ar II]$\lambda 6.98\mu$m displaying curves of different power-law index for both the dusty and dust-free models. Apparent in the diagram is the divergence of the two model sets at large values of ionization parameter ($U_0 > 10^{-2}$). Also conspicuous is the characteristic stagnation in the dusty models at these high values of ionization parameter. The power-law index of each curve decreases with increasing value of the Argon ratio for both sets of models, with -2.0 at the top to -1.2 for the bottom curve. The use of this diagram as an α diagnostic is clear, and the negligible reddening in this spectral region make this an ideal diagnostic for heavily obscured NLRs. Note that the Ne ratio has a large separation at low U_0, which is not obvious due to the different scales on each axis. This is as when the power law steepens, it drops the number of Ne V ionizing photons below a critical point and Ne VI becomes very weak.

With these two diagrams we have what appears to be rare in the UV and optical; a pure power-law diagnostic. Thus, if an active galaxies emission lines are measured for all three spectral regions, the use of line diagnostic diagrams can not only put strong constraints on the excitation mechanism but also the density, metallicity and ionizing spectrum of the emission line region.

4. Discussion

Through the diagnostic diagrams and comparisons with observations in the previous section we have demonstrated the validity of the dusty, radiation pressure dominated models as the paradigm for photoionization. The ability to reproduce both the observations and observed clustering of narrow line regions with similar parameters in diagnostic diagrams is strong evidence for the model. However, this work does not negate all work based upon the standard photoionization model. The active galaxies which were believed to be photoionized still appear to be so. The parameters estimated for these regions by the standard model are in general still correct. What this new paradigm does provide is a better diagnostic for the excitation mechanism, an explanation of how and where the standard model failed and better diagnostics to obtain more accurate estimates for the parameters that define these regions.

Neither does this new paradigm prove wrong the previous improvements upon the standard model, such as the $A_{M/I}$ model (Binette et al. 1996, 1997) and the "locally optimal emitting cloud" model (Baldwin, Ferland, Korista, & Verner 1995; Ferguson et al. 1997). Rather, this work, itself an improvement upon the standard model, provides a self consistent and self-contained physical basis for the emission of both high- and low-ionization lines without the necessary combining of clouds of different densities and ionization states.

As such, the dusty, radiation pressure dominated models can be considered as an explanation for the assumptions of the previous models. For example, the structure of the clouds in the dusty model, a depiction of which is displayed in figure 1 of Dopita et al. (2002), closely matches one of the geometrical distributions suggested for the $A_{M/I}$ models (Binette et al. 1996, figure 4b). The dusty model provides both the low ionization, ionization bounded component and the high ionization, matter bounded component within a single model, as shown in the ionization structure diagrams given in Paper 1. It does this through self-shielding, such that the high-ionization component sees the direct spectrum while the low ionization component near the ionization front sees the self absorbed spectrum. The dusty models also provide an explanation for the pressure difference between the matter bounded and ionization bounded components of the $A_{M/I}$ model through the effects of radiation pressure on dust. The final supporting point is that the dusty, radiation pressure dominated models also answers the problem emission line ratios that the $A_{M/I}$ models was originally created to solve. As shown in figure 13 and 15, the dusty model is able to produce strong He II/Hβ and strong [O III]λ4363/[O III]λ5007 (R_{OIII}), through the combination of ionization zones and dust photoelectric heating. The main distinction between the results of the dusty models and the $A_{M/I}$ models is also the major improvement; the stagnation in ionization parameter characteristic to the dusty model.

Just as the dusty, radiation pressure model does not prove incorrect the previous photoionization models, neither does it prove wrong the shock excitation models. The shock models and the photoionizing shock+precursor models require some form of mechanical energy input. In the absence of such an input the emission line clouds must be photoionized. However, if a jet or strong outflow is present within the AGN then shock excitation will play some part. In most cases the contribution from shock excited clouds is either indistinguishable or negligible compared the contribution from photoionized clouds. However in some cases, the emission from the shock excited clouds can become noticeable or even dominate the emission from photoionized clouds. Such a case is seen in the UV diagnostic shown in figure 5 when compared to the shock models and observations from figure 14 in Inskip et al. (2002a). Most of the radio galaxies are reproduced quite well by the dusty models. However a few of the observed high-z radio galaxies have a lower C III]/C II] ratio then is obtainable for the values of [Ne II]/[Ne V] seen. However, as discussed in Inskip et al. (2002a), these

outlying galaxies can either be easily fit by the shock+precursor model or a combination of shock+precursor and dusty model. Inskip et al. (2002a) also suggest that the balance between the two components depends upon the radio source size and hence jet structure, which may indicate some form of jet-cloud interaction. Even so, these observations demonstrate that more needs to be understood about how these two methods of excitation can coexist and how they interact.

5. Conclusion

First introduced in Dopita et al. (2002) the dusty, radiation pressure dominated photoionization model provides a self-consistent explanation for the emission from the narrow line regions of AGN. Within this work we have continued the examination of this new paradigm begun in Groves, Dopita & Sutherland (2003).

Through the comparison of observations on standard optical line diagnostic diagrams of Veilleux & Osterbrock (1987) and the UV diagnostics of Allen, Dopita, & Tsvetanov (1998) we have clearly demonstrated the validity of the dusty model as the new paradigm for photoionization. The dusty model, through the stagnation of the ionization parameter at large values, provides a simple explanation for the small variation of observed Seyfert NLR ratios. This stagnation is due to the effects of radiation pressure upon dust and is characteristic to these models. The significant point is that the dusty model is able to do this over both optical and UV ratios, without depending upon large variations in other parameters such as density or metallicity.

As well as verifying the dusty model,we have also explored the effects that the variation of density, metallicity and ionizing spectrum have upon both the new dusty paradigm and the standard photoionization models. With this exploration, we have demonstrated that several known line ratio diagrams can be possibly used as diagnostics of these three parameters.

In addition to the previously explored diagnostics, we have introduced several new line diagnostic diagrams, covering UV, optical and IR ratios. These diagnostics provide further tests for the dusty model as well as providing diagnostics for metallicity, density, ionizing spectrum and ionization parameter.

These results not only provide an explanation for what has not been a fully understood observation for years but also provide ways in which to understand further the processes involved in the NLR and extended NLR of AGN.

M.D. acknowledges the support of the Australian National University and of the Aus-

tralian Research Council through his ARC Australian Federation Fellowship and M.D. and R.S. acknowledges support through the ARC Discovery project DP0208445. The authors would like to thank the referee for their incisive and detailed comments which have much improved these papers.

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Table 1: Solar Abundance Set

Element	Abundance[a]	Element	Abundance[a]
H	0.000	Al	-5.51
He	-0.987	Si	-4.49
C	-3.61	S	-4.80
N	-4.20	Cl	-6.72
O	-3.31	Ar	-5.60
Ne	-3.92	Ca	-5.65
Na	-5.68	Fe	-4.54
Mg	-4.42	Ni	-5.75

[a]All abundances are logarithmic with respect to Hydrogen

Table 2. Depletion Factors

Element	Depletion[a]
H	0.00
He	0.00
C	-0.30
N	-0.22
O	-0.22
Ne	0.00
Na	-0.60
Mg	-0.70
Al	-1.70
Si	-1.00
S	0.00
Cl	-0.30
Ar	0.00
Ca	-2.52
Fe	-2.00
Ni	-1.40

[a]Depletion given as $\log(X/\mathrm{H})_{\mathrm{gas}} - \log(X/\mathrm{H})_{\mathrm{ISM}}$

Fig. 1.— The standard optical line diagnostic diagrams of Veilleux & Osterbrock (1987) (V&O) showing [N II]λ6583/Hα, [O I]λ6300/Hα and [S II]$\lambda\lambda$6717, 30/Hα versus [O III]λ5007/Hβ. The data points are from (VO87) and curves are as labelled in the keys.

Fig. 2.— UV diagnostics from Villar-Martin, Tadhunter, & Clark (1997, VTC97) and Allen, Dopita, & Tsvetanov (1998, ADT). Observations are from ADT, with asterisks represent high-z radio galaxies and triangles representing HST observations of three Seyfert 2 NLRs. Dust-free curves are marked with diamonds and dusty curves are marked with squares. Arrow represents magnitude and direction of 3 visual magnitudes extinction of models through a dusty screen.

Fig. 3.— UV diagnostic from ADT, demonstrating the effects of metallicity on the dusty model (a) and differences between the two models (b). α decreases from top to bottom for both dusty (square) and dust-free (diamond) model curves in (b). Observations (triangles) are from ADT. Reddening arrow as in figure 2a

Fig. 4.— UV diagnostic from ADT. Triangles represent HST observations from ADT, asterisks represent observations of Seyfert 2s from Koski (1978) and crosses represent observations of Seyfert 2s from Allen (1998). In (b) [O III]/Hβ increases with α for both model sets.

Fig. 5.— UV diagnostic diagram from Best, Röttgering, & Longair (2000b); Inskip et al. (2002a). Observations from Inskip et al. (2002a) with asterisks representing 3C galaxies and triangles 6C galaxies. In (b) α decreases with increasing C III]/C II]. Dusty model curves are marked with squares and dust-free models with diamonds.

Fig. 6.— UV diagnostic diagram of a dusty model with $Z = 2Z_{\odot}$ and $\alpha = -1.4$ as marked, showing curves of different density as labelled. Lines of constant ionization parameter are as labelled.

Fig. 7.— UV diagnostic diagram. Labelled as in previous diagram. This diagram demonstrates both a sensitivity to metallicity, due to the component of secondary Nitrogen, and a sensitivity to ionization parameter, revealing the stagnation due to radiation pressure on dust.

Fig. 8.— UV diagnostic diagram. Labelled as in previous diagram. Shows a strong metallicity sensitivity on both axis due to Nitrogen in each ration.

Fig. 9.— UV diagnostic diagram. Labelled as in previous diagram. Both metallicity and U sensitive as in figure 7.

Fig. 10.— Near-UV optical diagnostic diagram showing density variations on both the dusty (squares) and dust-free (diamonds) models. Lines of constant are U_0 marked on both. Density increases from top to bottom. Observations from Koski (1978) (asterisks) and Allen (1998) (crosses). Reddening arrow indicates magnitude and direction of 3 A_V extinction on models.

Fig. 11.— Optical diagnostic diagram suggested by Baldwin, Phillips, & Terlevich (1981) showing α variation in dusty and dust-free model. Curves and data marked as in previous diagram. Reddening arrow indicates $10A_V$ extinction here. α increases with [O III]/Hβ.

Fig. 12.— Binette et al. (1996) diagnostic diagram showing α variation in dusty and dust-free models. Models and data marked as in previous diagram. α increases from right to left.

Fig. 13.— Diagnostic diagram showing metallicity variations of dusty model. Curves and data marked as before.

Fig. 14.— Temperature sensitive diagnostic diagram showing density variation of both dusty and dust-free model curves. Density increases left to right at $U_0 = 10^{-3}$. In addition to the Koski (1978) (asterisks) and Allen (1998) (crosses) data, data from Tadhunter, Robinson, & Morganti (1989) is shown.

Fig. 15.— Helium - Oxygen diagnostic diagram showing density variations on dusty and dust free models. Density decreases from top to bottom for both sets of model curves.

Fig. 16.— Helium - oxygen diagnostic diagram with density variations of both models. Density increasing with increasing [O III]/Hβ. Symbols as before.

Fig. 17.— Helium - nitrogen diagnostic diagram showing metallicity variation of dusty model (a) and density variations of dusty and dust-free models (b). Symbols as before.

Fig. 18.— Density variations of both models in low ionization species diagnostic diagram. Density increases right to left for both sets of curves.

Fig. 19.— Metallicity variation of dusty model on nitrogen - sulfur diagnostic diagram.

Fig. 20.— [O II]$\lambda\lambda3727, 9\times$[S II]$\lambda\lambda6717, 30$ /[S II]$\lambda\lambda4067, 76\times$[O II]$\lambda\lambda7318, 24$ versus [O III]$\lambda5007$/Hβ diagnostic diagram showing density variation of dusty model.

Fig. 21.— Infrared diagnostic diagram showing curves of different α for the dusty model.

Fig. 22.— Comparison of the dusty (square) and dust-free (diamond) models in the Infrared diagnostic diagram. Curves of different α are shown, with α increasing from top to bottom for both models. Note the different scales on each axis.